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# Galaxy Formation and Dark Matter

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**Summary.** The challenge of dark matter may be addressed in two ways; by studying the confrontation of structure formation with observation and by direct and indirect searches. In this review, I will focus on those aspects of dark matter that are relevant for understanding galaxy formation, and describe the outlook for detecting the most elusive component, non-baryonic dark matter. Galaxy formation theory is driven by phenomenology and by numerical simulations of dark matter clustering under gravity. Once the complications of star formation are incorporated, the theory becomes so complex that the brute force approach of numerical simulations needs to be supplemented by incorporation of such astrophysical processes as feedback by supernovae and by active galactic nuclei. I present a few semi-analytical perspectives that may shed some insight into the nature of galaxy formation.

## 1 Introduction

Dark matter dominates over ordinary matter. The observations are compelling. Of course, by definition we do not observe matter if it is dark. Minimal gravitational theory is needed to take us from the observational plane to conclude that dark matter is required. Gravity has been tested over scales that range from millimetres to megaparsecs. Newton's description of gravity is perfectly adequate, apart from generally small deviations due to the curvature of space near massive objects, such as stars, or more radically, black holes. Einstein's theory of gravity tells us that gravity curves space and measuring this effect was one of the great triumphs of 20th century physics. Nevertheless, pending its direct detection, dark matter remains a hypothesis that depends, inevitably, on our having the correct theory of gravitation. For the remainder of this review, however, I will assume the reality of dark matter dominance on scales from galactic to those spanning the entire universe.

The standard (or concordance) model of cosmology has a predominance of dark energy, which amounts to 65% of the mass energy today whereas non-baryonic matter is 30%. In contrast, luminous baryons (mostly in stars) constitute 0.5% towards the total. An important component of the standard

model is the spectrum of primordial density fluctuations, measured in the linear regime via the temperature anisotropies of the CMB. This provides the initial conditions for large-scale structure and galaxy formation via gravitational instability once the universe is matter-dominated. Dark matter consequently provides the gravitational potential wells within which galaxies formed. The dark matter and galaxy formation paradigms are inextricably interdependent. Unfortunately we have not yet identified a dark matter candidate, nor do we yet understand the fundamental aspects of galaxy formation. Nevertheless, cosmologists have not been deterred, and have even been encouraged to develop novel probes and theories that seek to advance our understanding of these forefront issues.

Progress has been made on the baryonic dark matter front. Only about half of the baryons initially present in galaxies, or more precisely, on the comoving scales over which galaxies formed, are directly observed. We cannot predict with any certainty the mass fraction in dark baryons. Yet there are excellent candidates for the dark baryons, both compact and especially diffuse.

In contrast, we have at least one elegant and moderately compelling theory of particle physics, SUSY, that predicts the observed fraction of nonbaryonic dark matter. Unfortunately, we have no idea yet as to whether the required stable supersymmetric particles actually exist.

In this review, I will first describe the increasingly standard precision model of cosmology that enables us to provide an inventory of cosmic baryons. I summarise the current situation with regard to possible baryonic dark matter. I discuss how nonbaryonic matter has been successfully used to provide an infrastructure for galaxy formation, and review the astrophysical issues, primarily centering on star formation and feedback. I conclude with the outlook for future progress for nonbaryonic dark matter detection and galaxy formation.

## 2 Precision cosmology

Modern cosmology has emphatically laid down a challenge to theorists. A combination of new experiments has unambiguously measured the key parameters of our cosmological model that describes the universe. These include the temperature fluctuations in the cosmic microwave background, the large galaxy redshift surveys, gravitational shear distortions of distant galaxies by lensing, the studies of the intergalactic medium via the distribution of absorbing neutral clouds along different lines of sight and the use of distant Type Ia supernovae as standard candles. Cosmologists now debate the error bars of the standard model parameters. The ingredients of the standard model in effect define the model. These most crucially are the Friedmann-Robertson-Walker metric and the Friedmann-Lemaître equations, and the contents of the universe: baryons, neutrinos, photons, baryons, dark matter and dark energy. On these constituents is superimposed a distribution of

primordial adiabatic density (scalar) fluctuations characterised by a power spectrum of specified amplitude and spectral index. In addition, there may be a primordial gravity wave tensor mode of fluctuations. The number of free parameters in the standard model is 14, of which the most significant are:  $H_0$ ,  $\Omega_b$ ,  $\Omega_m$ ,  $\Omega_\Lambda$ ,  $\Omega_\gamma$ ,  $\Omega_\nu$ ,  $\sigma_8$ ,  $n_s$ ,  $r$ ,  $n_T$ , and  $\tau$ . One can also add an equation of state for dark energy parameter,  $w = -p_\Lambda/\rho_\Lambda$ , in effect really a function of redshift, and a rolling scalar (and possibly tensor) index,  $dn_s/d\ln k$ .

No single observational set constrains all, or even most, of these parameters. There are well-known degeneracies, most notably between  $\Omega_\Lambda$  and  $\Omega_m$ ,  $\sigma_8$  and  $\tau$ , and  $\sigma_8$  and  $\Omega_m$ . However use of multiple data sets helps to break these degeneracies. For example, CMB anisotropies fix the combination  $\Omega_m + \Omega_\Lambda$  if a Hubble constant prior is adopted, as well as  $\Omega_b h^2$  and  $\Omega_m h^2$ , and SNIa constrain the (approximate) combination  $\Omega_m - \Omega_\Lambda$ . Both weak lensing and peculiar velocity surveys specify the product  $\Omega_m^{-0.6} \sigma_8$ . Lyman alpha forest surveys extend the latter measurement to Mpc comoving scales, probing the currently nonlinear regime. Finally, baryon oscillations are providing a measure of  $\Omega_m/\Omega_b$ , independently of the CMB. Interpretation in terms of a standard model (Friedmann-Lemaitre plus adiabatic fluctuations) yields the concordance model with remarkably small error bars [1].

The flatness of space is measured to be  $\Omega_{total} = 1.02 \pm 0.02$ . Dark energy in the form of a cosmological constant dominates the universe, with  $\Omega_\Lambda = 0.72 \pm 0.02$ . The dark energy equation of state is indistinguishable from that of a cosmological constant, with  $w \equiv p_\Lambda/\rho_\Lambda c^2 = -0.99 \pm 0.1$ , this uncertainty holding to  $z \sim 0.5$ . Even at  $z \sim 1$ , the claimed uncertainty around  $w = -1$  is only 20 percent. Non-baryonic dark matter dominates over baryons with  $\Omega_m = 0.27 \pm 0.02$  and  $\Omega_b = 0.044 \pm 0.004$ . Most of the baryons are non-luminous, since  $\Omega_* \approx 0.005$ .

The spectrum of primordial density fluctuations is unambiguously measured both in the CMB and in the large-scale galaxy distribution from deep redshift surveys, and found to be approximately scale-invariant, with scalar index  $n_s = 0.98 \pm 0.02$ . One can also constrain a possible relic gravitational wave background, a key prediction of inflationary cosmology, by the tensor mode limit on relic gravitational waves:  $T/S < 0.36$ . It has been argued that a fundamental test of inflation requires sensitivity at a level  $T/S \gtrsim 0.01$  [2]. Neutrinos are known to have mass as a consequence of atmospheric ( $\nu_\tau, \nu_\mu$ ) and solar ( $\nu_\mu, \nu_e$ ) oscillations, with a deduced mass in excess of 0.001 eV for the lightest neutrino. From the power spectrum of the density fluctuations, the inferred mass limit (on the sum of the 3 neutrino masses) is  $\Sigma m_\nu < 0.4 \text{ eV}$ .

However one note of caution should be added. These tight error bars all depend on adoption of simple priors. If these are extended, to allow, for example, for an admixture of generic primordial isocurvature fluctuations, the error bars on many of these parameters increase dramatically, by up to an order of magnitude.

Clearly, the devil is in the observational details. Popular models of inflation predict that  $n \approx 0.97$ . Space is expected to be very close to flat, with  $\Omega =$

$1 + \mathcal{O}(10^{-5})$ . The numbers of rare massive objects at high redshift is specified by the theory of gaussian random fields applied to the primordial linear density fluctuations. The universe as viewed in the CMB should be isotropic. Any deviations from these predictions would be immensely exciting.

Suppose deviations were to be found. This would allow all sorts of possible extensions to the standard model of cosmology. One might consider the signatures of string relics of superstrings or transplanckian features in  $\delta T/T|_k$  [3]. Large-scale cosmology might be affected by compact topology or global anisotropy with observable signatures in CMB temperature and polarisation maps [4]. The initial conditions might involve primordial nongaussianity. Anthropically constrained landscape scenarios of the metauniverse prefer a slightly open universe [5]. Some of these features, and others, could be a consequence of compactification from higher dimensions.

### 3 The global baryon inventory

There are several independent approaches to obtaining the baryon abundance in the universe. At  $z \sim 10^9$ , primordial nucleosynthesis of the light elements yields  $\Omega_b = 0.04 \pm 0.004$ . At the epoch of matter-radiation decoupling,  $z \sim 1000$ , the ratios of odd and even CMB acoustic peak heights set  $\Omega_b = 0.044 \pm 0.003$ . At more recent epochs, Lyman alpha forest modelling of the intergalactic medium at  $z \sim 3$  as viewed in absorption along different lines of sight towards high redshift quasars at  $z \sim 3$  yields  $\Omega_b \approx 0.04$ . At the present epoch, on very large scales, of order 10 Mpc comoving linear regime equivalent, the intracluster baryon fraction measured via x-ray observations of massive galaxy clusters provides a baryon fraction of 15%. This translates into  $\Omega_b \approx 0.04$ . In summary, we infer that  $\Omega_b = 0.04 \pm 0.005$  and  $\Omega_b/\Omega_m = 0.15 \pm 0.02$ .

One's immediate impression is that, at least until very recently, most of the baryons in the universe today are not accounted for. The reasoning is as follows. The luminous content in the form of stars sums to  $\Omega_b \approx 0.004$  or 10% in spheroids, and  $\Omega_b \approx 0.002$  or 5% in disks. There is also hot intracluster gas amounting to  $\Omega_b \approx 0.002$  or 5%. Current epoch observations of the cold/warm photo-ionised IGM via the nearby Lyman alpha/beta forest at  $10^4 - 10^5$  K as well as CIII (at  $z \sim 0$ ) yield a much larger baryonic reservoir of gas,  $\Omega_b \approx 0.012$  or 30%. This gas is metal-poor, with an abundance of about 10% solar [6]. So far, we have only accounted for 50% of current epoch baryons.

The probable breakthrough, however, has come with recent detections of the warm-hot intergalactic medium at  $T \lesssim 10^5 - 10^6$  K at  $z \sim 0$ , observed in OVI absorption in the UV and especially via x-ray absorption via OVII and OVIII hydrogen-like transitions towards low redshift luminous AGN. Something like  $\Omega_b \approx 0.012$  or 30% of the primordial baryon fraction appears to be in this form, enriched (in oxygen, at least) to about 10% of the solar value [7]. We now have  $\gtrsim 80\%$  of the baryons accounted for today. The total baryon

content sums to  $\Omega_b = 0.032 \pm 0.005$ . Given the measurement uncertainties, this would seem to remove any strong case for more exotic forms of dark baryons being present.

However, the situation is not so simple. The Andromeda Galaxy and our own galaxy are especially well-studied regions, where dark matter and baryons can be probed in detail. In the Milky Way Galaxy, the virial mass out to 100 kpc is  $M_{\text{virial}} \approx 10^{12} M_\odot$ , whereas the baryonic mass, mostly in stars, is  $M_* \approx 6 - 8 \times 10^{10} M_\odot$ . The inferred baryon fraction is at most 8% [8]. Similar statements may be made for massive elliptical galaxies [9]. These in fact are upper limits as the dark mass estimate is a lower bound.

I infer that globally, there is no problem. Nevertheless the outstanding question is: where are the galactic baryons? Most of the baryons are globally accounted for. But this is not the case for our own galaxy and most likely for all comparable galaxies. We cannot account for a mass in baryons comparable to that in stars. It is possible that up to 10% of all the baryons *may* be dark, and that the dark baryons are comparable in mass to the galactic stars.

## 4 The “missing” baryons

There are several possibilities for the “missing” baryons. Perhaps they never were present in the protogalaxy. Or they are in the outer galaxy. Or, finally, they may have been ejected.

The first of these options seems very unlikely (although we return below to a variant on this). Consider the second option. The most likely candidates for dark baryons are massive baryonic objects or MACHOs. These are constrained by several gravitational microlensing experiments. The allowed mass range is between  $10^{-8}$  and  $10 M_\odot$ , and the best current limit on the MACHO abundance is  $\lesssim 20\%$  of the dark halo mass. In fact, one experiment, that of the MACHO Collaboration, claims a detection from some 20 events seen towards the LMC, most of which cannot be accounted for by star-star microlensing. The observed range of amplification time-scales specifies the mass of the lensing objects. The preferred MACHO mass is around  $\sim 0.5 M_\odot$ .

This mass favours an interpretation in terms of old halo white dwarfs. Main sequence stars in this mass range can be excluded. Current searches for halo high velocity old white dwarfs utilise the predicted colours and proper motions as a discriminant from field dwarfs, and set a limit of  $\lesssim 4\%$  of the dark halo mass on a possible old white dwarf component in the halo [10]. However even if this limit were to apply, an extreme star formation history and protogalactic IMF would be required. Observations at high redshift both of star-forming galaxies and of the diffuse extragalactic light background, combined with chemical evolution and SNIa constraints, make such an hypothesis extremely implausible.

If the empirical mass range constraint is relaxed, theory does not exclude either primordial brown dwarfs ( $0.01 - 0.1 M_\odot$ ), primordial black holes (mass

$\gtrsim 10^{-16} M_{\odot}$ ) or even cold dense  $H_2$  clumps  $\lesssim 1 M_{\odot}$ . The latter have been invoked in the Milky Way halo in order to account for extreme halo scattering events [11] or unidentified submillimetre sources [12]. However these possibilities seem to be truly acts of the last resort in the absence of any more physical explanation.

There is indeed another possibility that seems far less ad hoc. The nearby intergalactic medium is enriched to about 10% of the solar metallicity, and contains of order 50% of the baryons in photo-ionised and collisionally ionised phases. This strongly suggests that ejection from galaxies via early winds must have occurred, and moreover would inevitably have expelled a substantial fraction of the baryons along with the heavy elements. Supporting evidence comes from x-ray observations of nearby galaxy groups, which demonstrate that many of these are baryonically closed systems, containing their prescribed allotment of baryons.

There are candidates for young galaxies undergoing extensive mass loss via winds. These are the Lyman break galaxies at  $z \sim 2 - 4$ . Observations of spectral line displacements of the interstellar gas relative to the stellar component as well as of line widths are indicative of early winds from  $L_*$  galaxies [13]. Studies of nearby starburst galaxies, essentially lower luminosity counterparts of the distant LBGs, show that the gas outflow rate in winds is of order the star formation rate. The intracluster medium to  $z \sim 1$  is enriched to about a third of the solar metallicity, again suggestive of massive early winds, in this case from early-type galaxies. Hence the “missing” baryons could be in the IGM, with about as much mass ejected in baryons as in stars remaining.

The ejection hypothesis however has to confront a theoretical difficulty. Winds from  $L_*$  galaxies cannot be reproduced by hydrodynamical simulations of forming galaxies [14]. The momentum source for gas expulsion appeals to supernovae. SN feedback works for dwarf galaxies and can explain the observed outflows in these systems. However an alternative feedback source is needed for massive galaxies. This most likely is associated with AGN, and the ubiquitous presence of central supermassive black holes in galaxy spheroids.

First, however, I address a more pressing and not unrelated problem, namely given that 90 percent of the matter in the universe is nonbaryonic and cold, how well does CDM fare in confronting galaxy formation models?

## 5 Large-scale structure and cold dark matter: the issues

The cold dark matter hypothesis has had some remarkable successes in confronting observations of the large-scale structure of the universe. These have stemmed from predictions, now verified, of the amplitude of the temperature fluctuations in the cosmic microwave background that are directly associated with the seeds of structure formation. The initial conditions for gravitational instability to operate in the expanding universe were measured. The formation of galaxies and galaxy clusters was explained, as was the filamentary na-

ture of the large-scale structure of the galaxy distribution. Nor was only the amplitude confirmed as a prerequisite for structure formation. The Harrison-Zeldovich-Peebles ansatz of an initially scale-invariant fluctuation spectrum, later motivated by inflationary cosmology, has now been confirmed over scales from 0.1 to 10000 Mpc, via a combination of CMB, large-scale galaxy distribution and IGM measurements.

Despite these stunning successes, difficulties remain in reconciling theory with observations. These centre on two aspects: the uncertainties in star formation physics that render any definitive predictions of observed galaxy properties unreliable, and the detailed nature of the dark matter distribution on small scales, where the simulations are also incomplete.

The former issues include such observables as the galaxy luminosity function, disk sizes and mass-to-light ratios, and the presence of old, red massive galaxies at high redshift. These difficulties in the confrontation of galaxy formation theory and observational data are plausibly resolved by improving the prescriptions for star formation and feedback, although there are as yet no definitive answers. The latter issues require high resolution dark matter simulations combined with hydrodynamic simulations of the baryons including star formation and feedback.

I will focus first on the dark matter conundrums, and in particular on the challenges posed by theoretical predictions of dark matter clumpiness, cuspieness and concentration. Implementation of numerical simulations of dark halos of galaxies in the context of hierarchical galaxy formation yields repeatable and reliable results at resolutions of up to  $\sim 10^5 M_\odot$  in  $M_*$  halos. It is clear that the simulations predict an order of magnitude or more dwarf galaxy halos than are observed as dwarf galaxies. It is more controversial but probably true that the dark halos of dwarf galaxies and of barred galaxies do not have the  $\sim r^{-1}$  central cusps predicted by high resolution simulations. The dark matter concentration parameter, defined by the ratio of  $r_{200}$ , approximately the virial scale, to the scale length, within which the cusp profile is found, measures the cosmological density at virialisation, and hence should be substantially lower for late-forming galaxy clusters than for galaxies. This may not be the case in the best-studied examples of massive gravitationally lensed clusters, cf. [15]. There are also examples of early-forming massive clusters [16]

## 6 Resurrection via astrophysics

There are at least two viewpoints about resolving the dark matter issues, involving either fundamental physics or astrophysics. Tinkering with fundamental physics, in essence, opens up a Pandora's box of phenomenology. It seems to me that one should first take the more conservative approach of examining the impact of astrophysics on the dark matter distribution before advocating more fundamental changes. Of course if one could learn about fundamental physics, such as a new theory of gravity or higher dimensional dark

matter relics from dark matter modelling, this would represent an unprecedented and unique breakthrough. But the prospect of such revelations may be premature.

Astrophysical resolution involves two complementary approaches. One incorporates star and AGN feedback in the dense baryonic core that forms by gas dissipation. Massive gas outflows can effectively weaken the dark matter gravity, at least in the central cusp. These may include stellar feedback driving massive winds via supernovae augmented by a top-heavy IMF and/or by hypernovae, or the impact of supermassive black hole-driven outflows. Another mechanism that shows some promise in terms of generating an isothermal dark matter core is dynamical feedback, via a central massive rotating gas bar. Such bars may form generically and dissolve rapidly, but their dynamical impact on the dark matter has not yet been fully evaluated [17, 18, 19].

All of these are radical procedures, but some are more radical than others. To proceed, one has to better understand when and how galaxies formed. Fundamental questions in galaxy formation theory still remain unresolved. Why do massive galaxies assemble early? And how can their stars form rapidly, as inferred from the  $\alpha/Fe$  abundance ratios? Where are the baryons today? And if, as observations suggest, they are in the intergalactic medium, including both the photo-ionised Lyman  $\alpha$  forest and the collisionally ionised warm-hot intergalactic medium (WHIM), how and when is the intergalactic medium (IGM) enriched to 0.1 of the solar value? Can the galaxy luminosity function be reconciled with the dark matter halo mass function? Does the predicted dark matter concentration allow a simultaneous explanation of both the Tully-Fisher relation, the fundamental plane and the galaxy luminosity function? And for that matter, is the dark matter distribution consistent with barred galaxy and low surface brightness dwarf galaxy rotation curves?

The observational data that motivates many of these questions can be traced back to the colour constraints on the interpretation of galaxy spectral energy distributions by population synthesis modelling [20, 21]. The galaxy distribution is bimodal in colour, and this can be seen very clearly in studying galaxy clusters. The presence of a red envelope in distant clusters of galaxies testifies to the early formation of massive ellipticals. A major recent breakthrough has been the realisation from UV observations with GALEX that many ellipticals, despite being red, have an ongoing trickle of star formation. Most field galaxies and those on the outskirts of clusters are blue, and are actively forming stars.

The general conclusion is that there must be two modes of global star formation: quiescent and starburst. The inefficient, long-lived, disk mode is motivated by cold gas accretion and global disk instability. The low efficiency is due to negative feedback. The disk mode is relatively quiescent and continues to form stars for a Hubble time. The violent starburst mode is necessarily efficient as inferred from the  $[\alpha/Fe]$  clock. It is motivated by mergers, including observations and simulations, as well as by CDM theory. The high



efficiency is presumably due to positive feedback, but it is not clear how the feedback is provided.

## 7 What determines the mass of a galaxy?

The luminosity function of galaxies describes the stellar mass function of galaxies. It is biased by star formation in the B (blue) band but is a good tracer in the near-infrared (K) band. It is sensitive to the halo mass, at least for spiral galaxies, as demonstrated by rotation curves. There is a characteristic luminosity, and hence a characteristic stellar mass, associated with galaxies:  $L_* \approx 3 \times 10^{10} L_\odot$  and  $M_* \approx 10^{11} M_\odot$ . The luminosity function declines exponentially at  $L > L_*$ . This is most likely a manifestation of strong feedback.

Consider first the mass-scale of a galaxy. There is no difference in dark matter properties between galaxy, group or cluster scales, but there is a very distinct difference in baryonic appearance. Specifically, the baryons are mostly in stars below a galaxy mass scale of  $M_*$  and mostly in hot gas for systems much more massive than  $M_*$ , such as galaxy groups [22] and clusters. A simple explanation comes from considerations of gas cooling and star formation efficiency. It does not matter whether the gas infall initially is cold or whether it virialises during infall. The gas generically will be clumpy, and cloud collisions will be at the virial velocity. In order for the gas to form stars efficiently, a necessary condition is that the cooling time of the shocked gas be less than a dynamical time, or  $t_{cool} \lesssim t_{dyn}$ .

The inferred upper limit on the stellar mass, for stars to form within a dynamical time in a halo of baryon fraction  $f_b$  and mean density  $\rho_h$ , can be written as

$$M_* = A^\beta m_p^{2\beta} G^{-(3+\beta)/2} (t_{cool}/t_{dyn})^\beta f_b^{1-\beta} \rho_h^{(\beta-1)/2},$$

where the cooling rate has been taken to be  $\Lambda = A v_s^{2-3/\beta}$ , with  $\beta \approx 1$  being appropriate for metal-free cooling in the temperature range  $10^5 - 10^6$  K. This yields a characteristic mass  $M_*/m_p \approx 0.1 \alpha^3 \alpha_g^{-2} (m_p/m_e) (t_{cool}/t_{dyn}) \approx 10^{68}$ , where  $\alpha_g = G m_p^2 / e^2$ . This is comparable to the stellar mass associated with the characteristic scale in the Schechter fit to the luminosity function, and also the scale at which galaxy scaling relations change slope. However there is no reason to believe that the dynamical time argument gives as sharp a feature as is observed in the decline of the galaxy luminosity function to high luminosities. Additional physics is needed.

## 8 Outflows from disks

In the quiescent mode, the clumpy nature of accretion suggests that ministarbursts might occur. In fact, what is more pertinent is the runaway nature of

supernova feedback in a cold gas-rich disk. Initially, exploding stars compress cold gas and stimulate more star formation. Negative feedback is eventually guaranteed in part as the cold gas supply is exhausted and also as the cold gas is ejected in plumes and fountains from the disk, subsequently to cool and fall back.

Global simulations have inadequate dynamical range to follow the multiphase interstellar medium, supernova heating and star formation. The following toy model provides an analytical description of disk star formation. I assume that self-regulation applies to the hot gas filling factor  $1 - e^{-Q}$ , where  $Q$  is the porosity and is defined by

$$\begin{aligned} & (SN \text{ bubble rate}) \times (\text{maximum bubble 4-volume}) \\ & \propto (\text{star formation rate}) \times (\text{turbulent pressure}^{-1.4}). \end{aligned}$$

One can now write the star formation rate as [23]

$$\alpha_S \times \text{rotation rate} \times \text{gas density}$$

with  $\alpha_S \equiv Q \times \epsilon$ . Here  $\epsilon = (\sigma_{gas}/\sigma_f)^{2.7}$ , where the fiducial velocity dispersion  $\sigma_f \approx 20 \text{ kms}^{-1} (E_{SN}/10^{51} \text{ ergs})^{0.6} (200 M_\odot/m_{SN})^{0.4}$ . Here  $m_{SN}$  is the mass in stars formed per supernova and  $E_{SN}$  is the initial kinetic energy in the supernova explosion. The star formation efficiency  $Q\epsilon$  is

$$0.02 \left( \frac{\sigma_{gas}}{10 \text{ kms}^{-1}} \right) \left( \frac{v_c}{400 \text{ kms}^{-1}} \right) \left( \frac{m_{SN}}{200 M_\odot} \right) \left( \frac{10^{51} \text{ ergs}}{E_{SN}} \right).$$

The observed mean value is 0.017 [24]. Also, the analytic expression derived for the star formation rate agrees with that found in 3-D multiphase simulations [25]. In fact, the observed distribution of young stars in merging galaxies cannot be fit by modelling the star formation rate with a Schmidt-Kennicutt law, but requires the incorporation of a turbulence-like term [26], as incorporated in this simple model.

To extract the wind, one might expect that the outflow rate equals the product of the star formation rate, the hot gas volume filling factor, and the mass loading factor ( $f_L$ ). This reduces to  $\sim Q^2 \epsilon \dot{M}_*$ , or  $\dot{M}_{outflow} \approx f_L \alpha_S^2 \epsilon^{-1} M_{gas} \Omega$ . If  $Q$  is of order 50%, then the outflow rate is of order the star formation rate, but this evidently only is the case for dwarf galaxies. Once  $\epsilon \gg 1$ , the wind is suppressed.

This begs the question of how massive disks such as our own and M31 have depleted their initial baryon content by of order 50 percent. One cannot appeal to protospheroid outflows initiated by AGN (see below) to resolve this issue. Presumably baryon depletion in late-type massive disks (with small spheroids) must have occurred during the disk assembly phase. A collection of gas-rich dwarfs most likely assembled into a current epoch massive disk, and outflows from the dwarfs could plausibly have expelled of order half of the baryons into the Local Group or even beyond. However weak lensing studies

find that the typical late-type galaxy in a cluster environment appears to have utilised its full complement of baryons over a Hubble time [27], whereas an early-type galaxy may indeed have expelled about half of its baryons into the intracluster medium.

## 9 Outflows from protospheroids

Galaxy spheroids formed early. The inferred high efficiency of star formation on a short time-scale, as inferred from the  $\alpha/Fe$  enhancement, is suggestive of a feedback mechanism distinct from, and much more efficient than, supernovae.

The preferred context for such a mechanism is that of ultraluminous starbursts. Major mergers between galaxies produce extreme gas concentrations that provide an environment for the formation of supermassive black holes. The observed correlation between SMBH mass and the spheroid velocity dispersion suggests contemporaneous SMBH growth and coupled formation of the oldest galactic stars. The spheroid stars are old and formed when the galaxy formed. Hence the SMBHs, which account via the empirical correlation for approximately 0.001 of the spheroid mass, must have formed in the protogalaxy more or less contemporaneously with the spheroid. Supermassive black hole growth is certainly favoured in the gas-rich protogalactic environment.

Another clue is that both SMBHs, as viewed in AGN and quasars, and massive galaxy spheroids formed anti-hierarchically at a similar epoch, peaking at  $z \sim 2$ . Massive systems form before less massive systems. This could be a consequence of the same feedback mechanism, which necessarily must be positive in order to favour the massive systems. Supernova feedback is negative and is most effective in low mass systems. SMBH outflows provide an intriguing possibility for positive feedback that merits further exploration. What is lacking for the moment is quantitative evidence for the frequency with which AGN activity is associated with ultraluminous infrared galaxies. Nevertheless, AGN feedback seems to provide the most promising direction for progress.

A specific mechanism for positive feedback appeals to SMBH-induced outflows interacting with the clumpy protogalactic medium. Twin jets are accelerated from the vicinity of the SMBH along the minor axis of the accretion disk. These jets are the fundamental power source for the high non-thermal luminosities and the huge turbulent velocities measured in the nuclear emission line regions in active galactic nuclei and quasars. The jets drive hot spots at a velocity of order  $0.1c$  that impact the protogalactic gas. In a cloudy medium, the jets are frustrated and generate turbulence. The jets are surrounded by hot cocoons that engulf and overpressure ambient protogalactic clouds [28]. These clouds collapse and form stars. The speed of the cocoon as it overtakes the ambient gas clouds greatly exceeds the local gravitational velocity. In this

way, a coherent and positive feedback is provided via triggering of massive star formation and supernovae on a time-scale shorter than the gravitational crossing time [29]. The short duty cycle for the AGN phase relative to the longer duty cycle for the induced starburst must be incorporated into inferences from surveys about the frequency of associated AGN activity, if any.

Eventually, the input of energy must be highly disruptive for the proto-galaxy. When the SMBH is sufficiently massive, its Eddington-limited outflow drives out the remaining protogalactic gas in a wind. This curtailing of spheroid growth allows one to understand the quantitative correlation between SMBH mass and the spheroid gravitational potential [30]. Such negative feedback has been extensively applied in semi-analytic galaxy formation simulations to stop the gas cooling that otherwise results in excessive star formation in massive galaxies [31]. However the possibility of positive feedback has not hitherto been implemented.

## 10 ULIGs and spheroid formation

One may actually be seeing the AGN-triggering phenomenon at work in ultra-luminous infrared galaxies (ULIGs), which plausibly are the sites of spheroid formation and SMBH growth, as well as in powerful radio galaxies. High velocity neutral winds are found both in NaI [32] and in HI absorption [33] against the central bright nuclei. The rate of mass ejected in these superwinds is inferred to be a significant fraction of the star formation rate. Hence the baryon mass ejected is likely to be of order the stellar mass formed. This helps account for the baryon budget, with a complementary mechanism involving supernovae operative in dwarf galaxies and the precursor phase of massive disks.

A simple analytic model of this phenomenon may be constructed as follows. AGN momentum-driven outflow is inevitable once the mechanical momentum luminosity  $\dot{M}_w v_w$  or the radiative momentum luminosity  $L_{Edd}/c$  exceeds  $GMM_g/r^2$ , i.e.  $\sigma^4/Gf_b$ . Now  $\dot{M}_w \propto L_{Edd}$  and  $L_{Edd} = 4\pi GcM_{bh}/\kappa$ . In contrast, for a supernova-driven wind:  $\dot{M}_w = \dot{M}_* E_{SN}(m_{SN}\sigma v_c)^{-1}$ . Assume now that outflows lead to saturation of the star formation rate by exhausting the cold gas supply. I infer that  $M_{bh} = \frac{\kappa\sigma^4}{4\pi G^2}$ . The cooling criterion for star formation efficiency guarantees that this relation must saturate for black hole masses of around  $10^8 M_\odot$  if the relevant dynamical time-scale is gravitational (corresponding to a spheroid mass of  $\sim 10^{11} M_\odot$ ), but the reduced time-scale of AGN feedback increases the saturation limit to  $10^9 - 10^{10} M_\odot$ .

If this is correct, the ULIG/ULIRG phenomenon involves both spheroid formation and SMBH growth associated with the gas-rich proto-spheroid phase. The superwinds are AGN momentum-driven and are self-limiting, with the rate of mass ejected inevitably being of order the star formation rate. The SMBH-triggered associated outflows generate the  $M_{SMBH} \approx 10^6 \sigma_7^4 M_\odot$  relation, where  $\sigma_7$  denotes the spheroid velocity dispersion in units of 100 km/s.

This is in fact the observed correlation between  $M_{SMBH}$  and  $\sigma_g$  in both slope and normalisation, naturally cutting off above  $10^9 - 10^{10} M_\odot$ .

Supernova-triggered galactic outflows are prevalent until  $\sigma_{gas} \approx 100 \text{ km s}^{-1}$ ; at larger gas turbulence velocities, black hole outflow-initiated outflows must dominate. Self-regulation of jet outflow (positive) and star formation/SN (negative) feedback means that

$$\dot{M}_w \sim \dot{M}_* \sim L_{Edd}/\sigma v_w \propto \sigma^3 v_w^{-1} \lesssim v_w^2.$$

The predicted star formation rate is

$$\dot{M}_* \approx \dot{M}_w (m_{SN} v_c \sigma / E_{SN}) \approx L_{Edd} (m_{SN} v_c / E_{SN} v_w).$$

The star formation luminosity is predicted to be of order  $L_{stellar} \approx \dot{M}_* \epsilon_{nuc} f_{core}$ , where  $f_{core}$  is the mass in nuclear-burning stellar cores, and hence

$$L_{stellar}/L_{Edd} \approx \frac{\epsilon_{nuc} f_{core} E_{SN}}{m_{SN} v_c v_w \sigma}.$$

These represent predictions for ultraluminous star-forming galaxies at high redshift that should eventually be verifiable: the star formation rate is proportional roughly to the square of the wind velocity ( $\dot{M}_* \lesssim v_w^2$ ) and also to the square root of the quasar luminosity ( $\dot{M}_* \propto L_{Edd}^{1/2}$ ).

## 11 Observing cold dark matter: where next?

There is a motivated dark matter candidate, the lightest stable SUSY particle under R parity conservation, or WIMP. As yet, direct detection experiments have not found any unambiguous evidence for its existence. The Milky Way halo provides a laboratory par excellence for indirect WIMP searches via annihilations into high energy particles and photons.

The relic WIMP freezes out at  $n_\chi < \sigma_{ann} v > t_H \lesssim 1$ , corresponding to a temperature  $T \lesssim m_\chi/20k$ . The resulting CDM density is  $\Omega_\chi \sim \sigma_{weak}/\sigma_{ann}$ . Halo annihilations of the LSP occur into  $\gamma$  and  $\nu$ , as well as  $\bar{p}, p$  and  $e^+, e^-$  pairs. In fact, halo detectability may require clumpiness  $\langle n^2 \rangle / \langle n \rangle^2 \sim 100$ . SUSY modelling of parameter space supplies the relation between  $\sigma_{ann}$  and  $m_\chi$ . There is an uncertainty of some 2 orders of magnitude in the annihilation cross-section at specified WIMP mass. The WIMP mass most likely lies in the range 0.1-10 TeV, and annihilations provide possible high energy signatures via indirect detection for astronomy experiments. The only claimed evidence for direct detection relies on annual modulation in the DAMA NaI scintillation experiment, which is marginally viable for a spin-independent annihilation cross-section and a low WIMP mass ( $\sim 1 - 10 \text{ GeV}$ ) [34]. The uncertainties are large however, and improved data is urgently needed to assess these issues.

One can envisage progress on a variety of fronts. In particle theory, one can readily imagine more than one DM candidate. Why not have 2 stable

dark matter particles, one light, one heavy, as motivated by  $N = 2$  SUSY? If one took the light dark matter and any of the possible heavy dark matter detections seriously, one could have a situation in which the light (a few MeV) spin-0 particle is subdominant but a  $\sim 0.1 - 100$  TeV neutralino is the dominant relic [35].

Because a neutralino of mass  $\gtrsim 1$  TeV is beyond the range of the LHC or even the ILC, astrophysical searches for DM merit serious consideration and modest funding. In direct detection, one might eventually hope to see a modulated signal, due to the effect of the Earth's motion through directed streams of CDM [36]. The streams are generic to tidal disruption of dark matter clumps. As for indirect detection, the prospects are exciting, because of the many complementary searches that are being launched. Evidence of neutralino annihilations may come from searches for  $\gamma, \nu, e^+$  and  $\bar{p}$  signatures. Experiments under development include HESS2, MAGIC, VERITAS, GLAST ( $\gamma$ -rays), ICECUBE, ANTARES, KM3NET ( $\nu$ ), and PAMELA and AMS ( $e^+, \bar{p}$ ). Targets include the Galactic Centre, the halo and even the sun, where neutralino annihilations in the solar core yield a potentially observable high energy neutrino flux [37].

Refined numerical simulations will soon explore the impact of supernova and SMBH-driven outflows and bar evolution on the distribution and especially the concentration of CDM. A better understanding of intermediate mass black holes as well as the SMBH in the Galactic Centre could eventually provide “smoking guns” where spikes of CDM were retained: the enhanced neutralino annihilations measure CDM where galaxy formation began, 12 Gyr ago. Fundamental physics could be probed: for example a higher dimensional signature, Kaluza-Klein dark matter, would have a spectral signature and branchings that are distinct from those of neutralinos. The prospect of multi-TeV dark matter is another tantalising probe. This provides a challenge for SUSY but is possibly a natural and fundamental scale for any stable relics surviving from  $n=3$  extra dimensions.

## 12 Summary

Galaxy formation is still poorly understood despite its apparent successes. There is no fundamental theory of star formation. One can adopt various empirical parameters and functions, incorporate plausible assumptions and prescriptions and add new ingredients until satisfactory explanations are obtained of any specified observations. Beautiful images are often simulated at such vast cost in computer time that it is impossible to test the robustness of the favoured location in multidimensional parameter space.

Dark matter searches are not in a much healthier state. They rely on plausible assumptions about the dark matter candidates and on the theory of gravity. There is a vast parameter space that admits undetectable particles,

such as the gravitino. One has to hope that the likely culprit has electromagnetic couplings.

This is the down side. Bayesians would abandon hope at this juncture, and argue that more science return per dollar will come, for example, by sending men to Mars. Yet to conclude on a more positive note, there is every prospect that potential advances in supercomputers, with virtually no limit to the size of future simulations, will allow us to reproduce our local universe in detail, thereby providing a firmer basis for extrapolation to the remote past. And this extrapolation could be largely phenomenological, driven by the data flow from ever larger and more powerful telescopes that peer further into the universe and hence into our past.

Likewise, the forthcoming LHC and the eventual construction of the ILC will pose tighter constraints on the underlying particle physics that provides the infrastructure for speculations about dark matter. With any luck, supersymmetry will be discovered, thereby setting dark matter candidates on a far firmer footing. And the complementary experiments in direct and in indirect detection should, within a decade, probe all of the allowable SUSY parameter space.

This is an exciting moment in cosmology. We are at the threshold of confirming a standard model, which seems boring and even ugly. Yet the prospect beckons of finding new physics in the unexpected deviations from the model. A convergence of particle physics and astronomy, in experiment and in theory, will inevitably lead us onto uncharted territory. There can be no greater challenge than in deciphering what awaits us.

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